9_4 # Droplet Clustering via Droplet Spacing Measurements from RICO

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1. Introduction

The possibility of cm-scale structure in cumulus-cloud droplet-concentrations has been investigated via observations both *in-situ* (Baker 1992, Chaumat and Brenguier 2001, Kostinski and Shaw 2001, Pinsky and Khain 2001) and remote (Baker and Brenguier 2006, Erkelens et al. 2001), and via models both laboratory (Lazaro and Lasheras 1989, Squires and Eaton 1991), and numerical (Fung and Perkins 1989, Crisanti et al. 1992, Vaillancourt and Yau 2000). The consequences of such small-scale structure may or may not have significant implications for the basic cloud physics of droplet growth by condensation and growth by collision and coalescence (Shaw et al. 1998, Brenguier and Chaumat 2001). However, the question of whether cm-scale structure really exists to a significant extent has been the subject of debate (Grabowski and Vaillancourt 1999) and at least one workshop (Shaw 2002) and has remained open for more than two decades. The question has remained open for several reasons. The experiments cannot model the high Reynolds number of cumulus clouds and are therefore suggestive but not conclusive. The *in-situ* measurements have never been substantiated with an independent measurement. The subject of this work is to address the later reason.

The possibility of observable small scale (~1 cm) droplet clustering was first presented by Baker (1992) using a standard Forward Scattering Spectrometer Probe (FSSP, Dye and Baumgardner 1984) equipped to record droplet spacing. A statistical test was used to demonstrate the existence of centimeter scale structure in the recorded data. However, the FSSP sample tube may have been responsible for creating the structure. With the FSSP sample volume several cm downstream of the sample tube inlet, a tube of a couple cm diameter, the possibility exists that shadowing and locally produced vortices are causing the structure. The 2D-S (Lawson et al. 2005) and PDI (Chuang et al. 2005, Bachalo and Houser 1984, Bachalo and Sankar 1996) do not have sample tubes, measure droplet spacing, and along with the Fast-FSSP (FFSSP Brenguier et al. 1998), were installed and operated on the NCAR C-130 aircraft during the Rain In Cumulus over the Ocean experiment (RICO, Rauber et al. 2004). The FFSSP has both improved electronics and optics compared to the standard FSSP. The FFSSP uses the same sample tube however. Data from all three instruments are analyzed and compared to determine whether detectable small-scale structure exists in RICO cumulus clouds. We cautiously report that the cm structure may be real.

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2. Method (The Fishing test)

The fishing test (Baker 1992) is used to investigate the small-scale structure of droplet concentrations in RICO clouds. To review, the fishing statistic (F) is calculated at many length scales (L). A value of F greater than three is a highly significant indicator that the statistic's null hypothesis of homogeneous droplet concentration is false. F is plotted versus L to yield information on the scale of the inhomogeneous structure. The case of interest occurs when there is relatively little structure on the large scales (~1 - ~100 m) but significant structure on small (typically ~1 cm) scales. In this case, a peak in F versus L occurs at about one half the length scale of the structure (e.g., Figs 2 - 4). The large-scale concentration variations must be much weaker than the small-scale concentration variations for this to occur because the sensitivity of F increases with the scale of the structure. The sensitivity also increases with the number of droplet spacing observations (N) and with decreasing mean droplet spacing. The latter tendency is as much a function of the sample area of the probe as it is a function of the actual droplet spacings in the cloud. The mean droplet spacing of the measurements is inversely proportional to the probe's sample area and therefore also the probe's data rate.

A model was developed similar to that used by Baker (1992) to define the properties of the statistic. In this study, the model is used to investigate the potential sensitivity of each instrument as well as to perform quality control on the processing software for each instrument. The model simulates the same average data rates as the real data but in a model cloud that contains blocks of 5 cm length. These 5-cm blocks have alternately higher and lower rates, i.e., droplet concentrations, thus simulating structure on the same scale as indicated by the fishing test and providing an estimate of the concentration differences across those structures.

In the following section, each instrument will be discussed, in terms of sensitivity, spurious events, and the indication of centimeter scale structure. To summarize briefly in advance:

- The FFSSP data indicates structure on cm-scales if all events are used but not if only qualified in-DOF events are used. In this case, however, noise events must be ignored. At times cm-scale structure is indicated in the real data. The model is used to estimate a concentration difference of that structure, which is then used to estimate expectations for the other probes, given their varying data rates.
- The PDI data rate is too low to reveal information on cm-scales in the RICO data set at the concentration differences inferred from the FFSSP data and the model simulations.
- The 2D-S data rate is considerably faster than the FFSSP's and as such is sufficient to detect cm-scale structure, which sometimes it does after also eliminating spurious noise-like events.

3. Results

3.1 One large core

Figure 1 shows the concentration time series from each instrument through a cloud with a large core. An especially flat section lasting 3.4 seconds or about 375 meters at the C-130's airspeed of about 110 ms^{-1} is also indicated by shading on the figure. This is our primary section of data for the preliminary analysis. The penetration was near cloud top at about 5.5 Kft in altitude.

We begin with the FFSSP, showing that using all the events (except spurious noise events) yields a cm-scale peak in the F-vs-L plot. **Figure 2a** shows the result of applying the fishing test to the chosen section of data using only the 2578 particles that were qualified as in Depth of Field (DoF). The test does not reveal any significant structure. That is, within the sensitivity of the test, the section is homogenous in droplet concentration. Using all 43058 particle events, however, indicates the presence of significant small scale structure. **Figure 2b** shows the result of fishing on all the events. There is a spurious peak at L of about 100 μm. That the peak is spurious is apparent in the distribution of inter-arrival times (**Figure 2d** red trace) where it is seen that excess, very short inter-arrival-time events occur. The distribution should be approximately exponential, which would be a straight line on the log-linear plot. These excess events are likely electronic noise and, as such, can be removed by ignoring the events with small pulse amplitudes. **Figure 2d** (green trace) shows the inter-arrival time distribution ignoring those smallest amplitude events, which leaves 33658 events. The excess, short inter-arrival-time events are gone and the fishing test no longer indicates a peak at L of about 100 μm (**Figure 2c**). There is, however, a significant peak at L of a few cm, which is consistent with the earlier results of Baker (1992).

The focus of this work is to determine whether this peak is real or spurious. That is, is it substantiated by the newer instruments? First, there is the question of why the peak does not show up using only the FFSSP in-DoF particles. An answer is suggested by using the model, which indicates that concentrations, for the alternating 5-cm blocks, of 1.25 to 0.75 of the mean rate typically yields a peak F value of about 8 at L of about 2.5 cm (**Figure 3**), similar to the real data. While a subset of the data, representing the in-DoF events, does not indicate any structure. The data rate appears be too low, for the in-DOF events, for the fishing test to be sensitive to the magnitude of structure suggested by the set of all events and the model. Other possible explanations are discussed in the following section.

During the same 3.4 seconds, the PDI observed 645 qualified particle detection events out of 1578 total events and no structure is indicated by the fishing test. This data rate, is even lower than the in-DOF particle rate for the FFSSP. Therefore, we cannot expect to detect cm-scale structure with these data at the degree of structure suggested by the FFSSP data and the model.

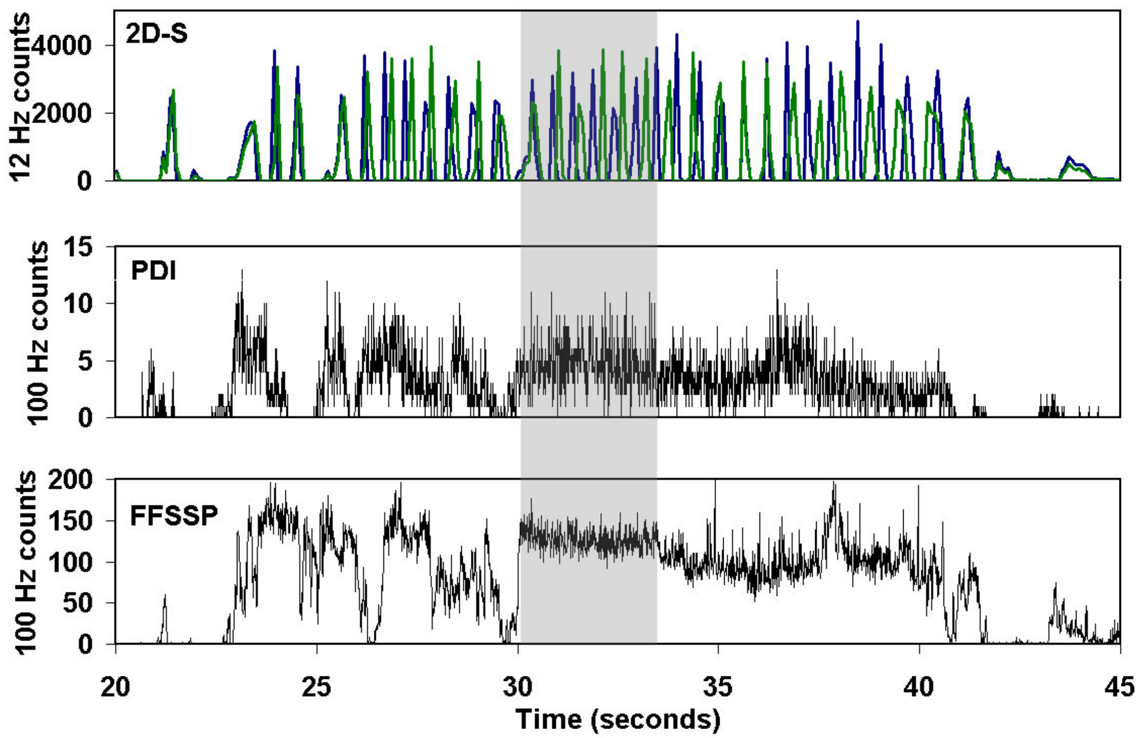

Figure 1: Time series of particle counts for both channels of the 2D-S, the PDI and the FFSSP, from RICO research flight 19 on 24 Jan 2005. The gray area designates the region used for analysis of droplet spacing data. The time is in seconds since 13:06:50.5 GMT. The 2D-S time series is intermittent because in such dense cloud the data recording system cannot keep up with the rate of data acquisition, so the probe alternates between periods of acquiring data and periods of catching up on recording the data during which no new data is acquired.

Because the 2D-S data is intermittent, we do not process it for the continuous 3.4-second period as we did for the FFSSP and PDI. However, the data rate is higher and yields on the order of 3000 events in about 40 ms which during the period of interest was the typical length of time that the 2D-S could collect data before going into overload. For this rate of data and the degree of structure suggested by the FFSSP data and the model (alternating concentrations at 1.25 and .75 of the mean), the model predicts that the 2D-S data should indicate a cm-scale peak with a maximum F value between about 4 and 8. **Figure 4a** shows one particular realization, an approximate expectation of what the 2D-S should show if the FFSSP results are real instead of being caused by spurious effects. **Figure 4** also shows the results of applying the fishing test to the real 2D-S data for a 43 ms period within the 3.4 s period that the FFSSP data was analyzed. Similar to the FFSSP data, there are spurious events that cause the indication of ~100 μm scale structure, when all the events are used. There is a peak at $L \approx 50$ μm in the F vs L plot (**Figure 4b**). In this case, we suspect broken images due to out of focus diffraction effects rather than electronic noise, or, a combination of both. Like for the FFSSP data, the spurious effect is easily detected by the excess of very short inter-arrival-times (**Figure 4d** red trace). They are easily removed by simply ignoring events with such short inter-arrival-times. Here we ignored all events with inter-arrival times less than 6 ticks and subtract 5 from all remaining inter-arrival times before analysis. Baker (1992) showed this technique is valid and used it with the original FSSP data to reduce the effect of that instrument's dead time and coincidence phenomena.

Figure 4c shows the fishing test result after this procedure, indicating a peak at 2 to 5 cm and with a magnitude equal to that expected from the FFSSP data and the model (figure 4a). Thus, it appears that the 2D-S data supports the hypothesis that the cm-scale structure, revealed by the FFSSP and earlier FSSP data, is a real phenomenon. Alternative hypothesis are discussed in the following section.

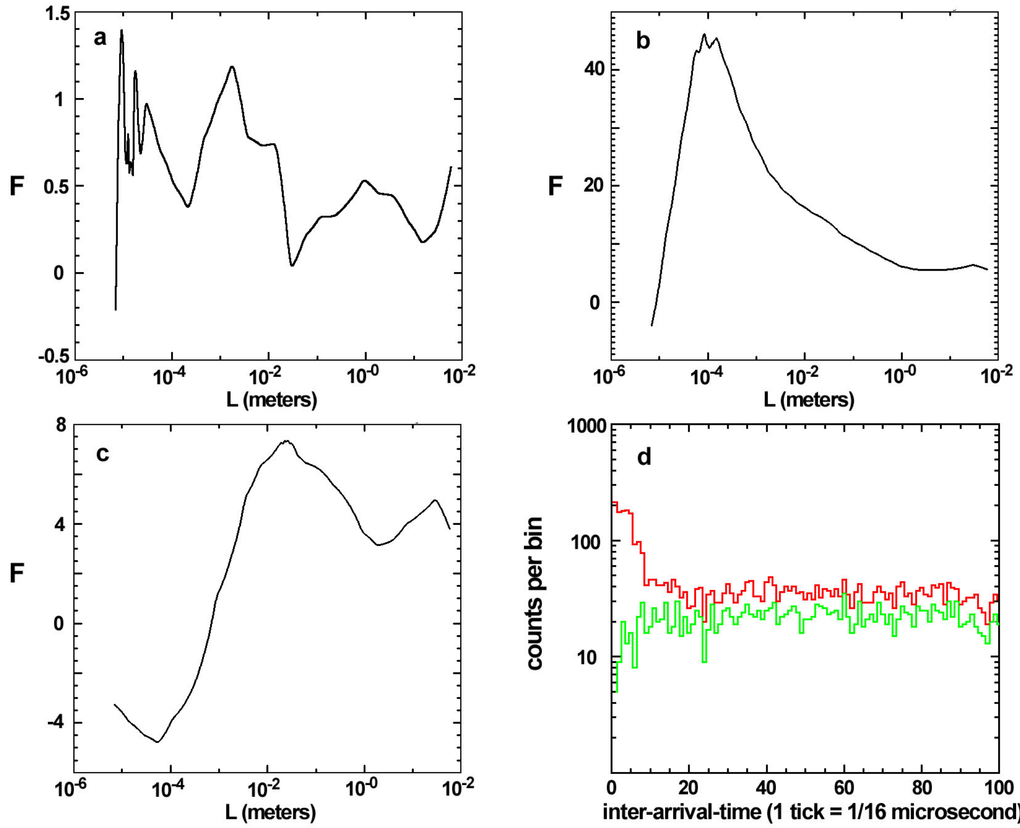

Figure 2: Fishing test results using FFSSP data. a) is using only in-DoF particles, b) is using all particles including apparent noise events, c) is all particles with noise events and likely, some real particles removed by ignoring small pulse height events, d) is the small end of the inter-arrival-time distributions for the all events case (red) and all events minus the smallest pulse height events case (green).

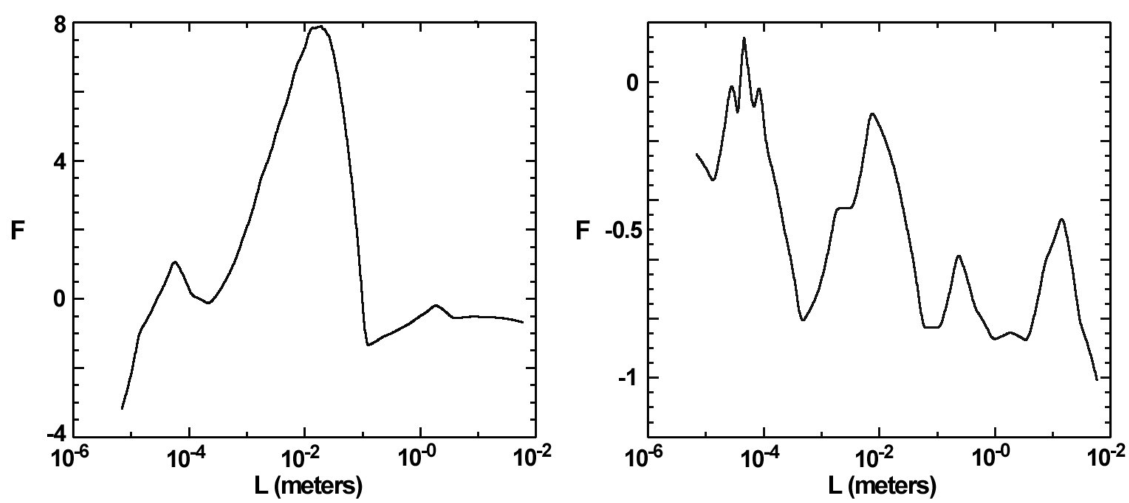

Figure 3: The results of the fishing test applied to simulated data approximating the real data presented in figure 2. Left uses all 33221 events while on the right uses only a subset of 2563 events.

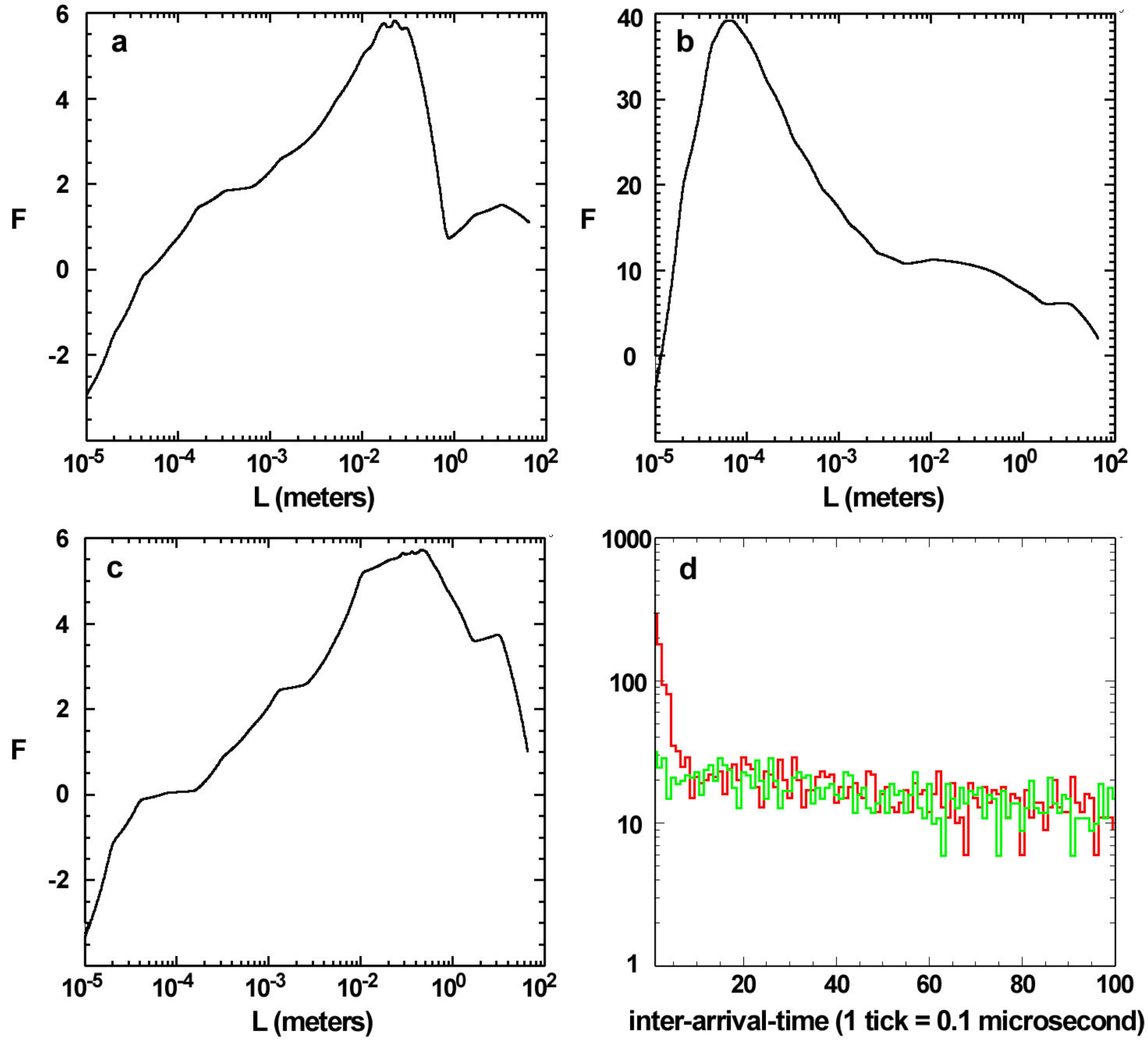

Figure 4: Fishing test results for the 2D-S: a) is an approximate expectation if the FFSSP data results are real, b) uses all the data events without alteration and has a spurious peak at about 50 μm, c) shows a cm-scale peak once the spurious effect is removed by ignoring the shortest inter-arrival events and altering the remaining times as described in the text. d) is the small end of the inter-arrival-time distributions for the all events case (red) and all remaining events with alteration case (green).

3.2 Other clouds

Above we focused on one exceptionally large cloud section to compare the results of all three instruments in the most favorable situation for detecting small-scale inhomogeneities. The favorable period was a long time period without large-scale structure in the droplet concentration. Some preliminary results from other cloud sections are presented here. Although preliminary, the results are worth reporting as they facilitate discussion of interpretations in the follow section.

At the altitude of 5500 Kft it is not difficult to find regions indicating cm-scale structure as presented above. A second example was found from 12:45:51.781 to 12:45:51.808 in the 2DS data. The particles were limited to slightly smaller sizes and the data rate was slightly higher. **Figure 5** (green trace) shows the Particle Size Distributions (PSDs) for this period and two additional periods yet to be discussed.

At an altitude of 2.6 Kft the droplets were significantly smaller (**Figure 5** blue trace) and it was considerably more difficult to find indication of cm-scale structure. One example was found after analyzing about a dozen periods. On 16 Dec 2004, the collision and coalescence process was much less active and the droplets even smaller (**Figure 5** red trace). After analyzing about a dozen periods on this day, no indication of cm-scale structure was found.

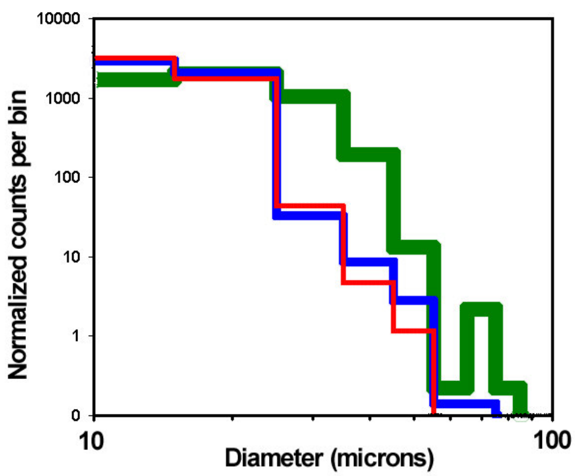

Figure 5: PDSs from the 2D-S for three different periods. Green is at 5.5 Kft on 24 Jan 2005. Blue is at 2.6 Kft on 24 Jan 2005 and red is at 2.7 Kft on 16 Dec 2004. Each distribution is in counts per bin, normalized by its total counts and times 10000. This allows comparison while leaving each with roughly the correct order of magnitude of counts per bin.

4. Discussion

The first goal of analyzing 2D-S and PDI droplet spacing data was to determine whether the cm-scale structure previously observed in FSSP and FFSSP droplet spacing data is a real effect in cumulus clouds or a spurious effect of the inlet sample tube. The existence of a similar peak in the 2D-S data suggests that it is a real effect. However, the possibility of other spurious effects that could cause both instruments to indicate false cm-scale structure must still be considered.

The trend for the cm-scale structure to be more readily found where the droplets are larger is consistent with expectations if it is a real effect, due to the inertia of droplets causing them to be thrown out of vortices. It would also be consistent if drop splashing were the cause. The effect of precipitation drops splashing on both the NCAR FSSP and the 2D-S is the subject of investigation reported in P2.29 of these proceedings. In that study, splashing events are clearly recognizable on the imaging probe (2D-S). Such clearly demonstrable splashing is not occurring in the cloud regions presented herein. Nevertheless, the possibility of a much more subtle effect due to splashing of the particles that comprise the large end of the PSD must be considered. Similarly, it seems unlikely that electronic noise exists at 10-100 KHz, the frequency range that would lead to cm-scale structure at 110 ms^{-1} air speed, which would affect both instruments similarly, especially given that higher frequency noise does occur and has been removed. Nevertheless, the possibility must be rigorously investigated before making firm conclusions

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